Knowledge based representation and operations assessment of space transportation system architectures

Alex J. Ruiz-Torres [a,*], Edgar Zapata [b,1], Kazuo Nkatani [c,2], Marcella Cowen [d,3]

[a] *Department of Information and Decision Sciences, College of Business Administration, University of Texas at El Paso, El Paso, TX 179968, USA*
[b] *Systems Engineering Branch, NASA Kennedy Space Center, KSC, FL 32899, USA*
[c] *Computer Information Systems and Decision Sciences Department, Lutgert College of Business Administration, Florida Gulf Coast University, Fort Myers, FL 3xxxx, USA*
[d] *Blue Frog Technologies, 806 Turney, El Paso, TX 79902, USA*

Abstract

Achieving the goals of safe and cost effective space transportation systems requires the development of new methods and tools that allow leap-frog improvements in the conceptualization, design, development, production, and operation of these systems. This paper reports on a modeling methodology aimed at the knowledge based representation and operational assessment of space transportation systems to be used during early stgqcaes of design with the objective of improved design via estimation of their ground operations and performance. The model uses knowledge based logic and equations combined with a process database to determine the appropriate ground processes and their duration, allowing the estimation of operational measures of performance such as labor, cycle time, and flight rate.
© 2006 Published by Elsevier B.V.

Keywords: Space transportation systems; Knowledge based systems; Operations modeling; Complexity; Reusability; Reliability

1. Introduction

There is a clear need for radical changes in space transportation systems design processes and understanding if the objectives of the United States to return to the Moon and for the human exploration of Mars are to be achieved. In addition, the continued exploration of space and experimentation in zero gravity may lead to discoveries that can serve all humankind. Further, low cost and reliable access to space allows the continued development of global communication systems, promotes new space related ventures such as space tourism and furthers the evolution to ultra-fast aero-spaceplanes that could reduce the time required to travel from North America to Oceania to just a few hours.

Multiple research and development efforts have been directed at achieving improvements in the reliability and cost of space transportation systems. These efforts are of a variety of types, from hardware developments, for example research into new propulsion systems and new thermal protection materials, to architectural developments, for example studies that investigate the approach and technologies required to achieve the low cost/high reliability objectives. Projects such as the Reusable Launch Vehicle Program (RLV) and the Highly Reusable Space Transportation Study (HRST) are recent examples of NASA's efforts into the developments of technologies and approaches that will lead to improvements in cost and reliability [1].

Other efforts have been directed at the assessment of technologies and approaches through the development of models, particularly knowledge/data models that predict

---

* Corresponding author. Tel.: +1 915 747 5970.

E-mail addresses: aruiztor@utep.edu (A.J. Ruiz-Torres), edgar.zapata-1@nasa.gov (E. Zapata), knakatan@fgcu.edu (K. Nkatani), m.cowen@blue-frog.biz (M. Cowen).

[1] Tel.: +1 321 867 6234 (E. Zapata).
[2] Tel.:+1 239 590 7364 (K. Nkatani).
[3] Tel.: +1 915 307 1323 (M. Cowen).

the behavior and performance of the space vehicle system [2]. In the past, most of these efforts focused on the assessment of manufacturing and development costs, and ignored life cycle cost factors related to operations. Even recent developments such as the Space Taxi [3] fail to address the operational requirements and costs of space transportation architectures. However, the tide may be turning as awareness has grown that the cost of operating the Shuttle system far exceeds the development and manufacturing costs. The development of models that can assess the ground operations of future transportation systems is critically important if the goal of low cost access to space is to be achieved.

The operational assessment of future space transportation systems is knowledge based; there are no proven formulas or procedures that will generate an operational ground process for a space transportation system. This is so for various reasons including the complexity of the systems/technologies and the variety of these technologies, which makes it impossible to develop a single method for estimation of operations. The situation is further worsened given that Shuttle data is often spotty (not available in a systematic way through all systems and functions) and frequently held by NASA contractors who for reasons of competition, or lack of a requirement to do so, do not make it available for external users.

The assessment of ground operational requirements for new space vehicles is critical as exemplified by the Space Shuttle system. During conceptual design it was envisioned that the Shuttle's maintenance and servicing processes were to be simple and able to maintain an expected flight rate of 10 flights per year per vehicle. It was also envisioned that the maintenance, servicing, and inspection processes would require little infrastructure. Additionally, payload integration would be simple, involving very little labor. The Space Shuttle was supposed to provide significant cost reductions when compared with its predecessors systems, but this depended on a dramatic flight rate increase that was never achieved [4]. These flight rate and costs goals were never met due to the complexity of the ground infrastructure required to meet the servicing, inspection, and checkout required by the equally complex vehicle design.

Therefore, ground operations, measured primarily by variables such as vehicle cycle time (time between launches), direct labor hours and support hours, maintenance and repair costs, and facilities and infrastructure costs must be estimated, with as much accuracy as possible in order to drive and focus the development of vehicle systems that can meet the low cost and associated high flight rate objectives. This paper reports on a knowledge based approach that estimates the operations of future reusable transportation systems utilizing the operations knowledge of NASA and its contractors. The system uses a vehicle knowledge representation based on constructs that are linked to a process database serving as a baseline set of operations. The

described modeling approach was implemented in a tool used by vehicle designers at NASA and its contractors.

The remainder of this paper is organized as follows: Section 2 provides a description of the design and assessment stages for launch vehicles and Section 3 discusses the knowledge based representation of space vehicles for operations assessment. Section 4 presents the knowledge based process used in the operations assessment, while Section 5 briefly describes the implementation of the models in a software application called SAGE. Section 6 presents the conclusions and future work.

2. Space transportation systems design and assessment

In the design of space vehicles there are a considerable number of complex systems that are typically designed independently at the early stages, but interact as the design develops. The design process starts after mission/program requirements are set, driving a design process that moves from conceptual design, to detailed design and development, to manufacturing and then to operations, the last typically responding to the actual vehicle produced and it's capability as depicted in Fig. 1. As in any design process, the ability to change the design diminishes as more detailed designs are developed and investments are committed. The significance of understanding the design process lies in the effect of using downstream knowledge in the early phases of the process, in other words, how much manufacturing design and operations knowledge is used during conceptual and detailed design. This is highly significant due to the fixed and variable costs associated with both the manufacturing and operation phases of space transportation systems, phases that have been relatively ignored in the past during a more flight performance focused detailed design.

Different types of design knowledge are required to complete mission and life cycle assessments for new vehicles. The first phase includes knowledge and engineering models that capture flight capabilities. These models determine if the system has the required mechanical and flight characteristics, in essence answering the question, will it get to
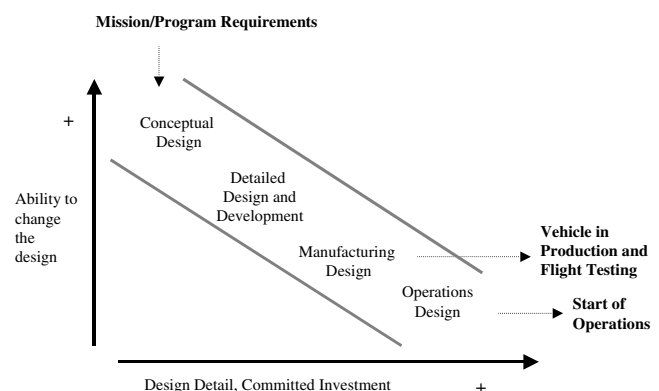

Fig. 1. Space vehicle architectures design process overview.

KNOSYS 1557

22 June 2006   Disk Used

ARTICLE IN PRESS

No. of Pages 8, Model 5+

Jayalakshmi (CE) / Karthikeyan (TE)

A.J. Ruiz-Torres et al. / Knowledge-Based Systems xxx (2006) xxx–xxx

3

space and back given its propulsion approach and weight. The second phase assesses the design in terms of development costs, determining the time frame and investment required to develop the systems. These models require designers to specify the technologies to be used and the approaches to be used for their development. The next phase involves the assessment of the manufacturing processes and investment. Both the design and development assessment and the manufacturing assessment includes program duration and expected flight rate in order to allocate investments across the number of vehicles to be produced and determine improvement effects related to economies of scale and learning curve. The fourth phase assesses the design in terms of ground operations. These models assess the time and cost of ground operations per vehicle and for a complete fleet based on the complexity and reliability of the design and the estimated flight rate capability. Designers must provide information into the maintainability approach, interfaces between systems, for example sharing of liquids or gases, and information into the way multiple stages of the vehicle will be integrated. This is the area where the presented knowledge based model fits in.

This research presents a modeling approach for the knowledge-based representation and estimation of ground processes for a space vehicle architecture. The objective is to provide those involved in the earlier phases of space vehicle systems design, primarily during the conceptual design phase, with operations design knowledge by providing insights into the effect of vehicle design decisions on ground operations, not only in terms of times, but also in terms of the type and number of ground activities required for processing. Providing conceptual designers with this knowledge supports a global view of the system that is cost effective in terms of life cycle costs. It is important to note, that given we have had only one reusable system in operation, a significant amount of the required knowledge must be based on opinions and extrapolations rather than on actual observations and data. Therefore it is important in the development of the knowledge to use and integrate multiple sources with diverse backgrounds and opinions.

3. Knowledge based vehicle representation

In a ground operations assessment model it is necessary to represent a vehicle by those characteristics that have been recognized by operations experts as having an effect on the ground processes and that are decided at the conceptual and early phases of the detailed design level. The effect of this is that design decision will be linked to operations early on, and that additional decisions related to operations must be made earlier than in the past. This is a significant benefit as it forces vehicle designers to design not only for development and manufacturing assessment, but also for operations assessment.

A space vehicle system is inherently a very complex system [5], therefore models must be flexible and allow the complexity to be represented and not eliminated. The proposed model defines a space vehicle system at two structural levels during the conceptual design process: integrated vehicle and separate flight elements (FE). For example in the Space Shuttle (Fig. 2), the integrated vehicle is made up by three flight elements: the Orbiter, the external tank (ET) and the solid rocked boosters (SRB). The SRB's are an FE that is used during early ascent and then jettisoned after the fuel is spent (stage 1 of flight). The ET is another FE and a set of tanks that stores the propellant and oxidizer used by the Orbiter's main engines during ascent. The ET is jettisoned after the tanks are empty or the desired altitude has been reached (stage two of flight). Finally, the Orbiter is an FE that reaches orbit carrying a crew and payload, and then returns to Earth to repeat the cycle. Of the three FE's just described, the SRBs are partially reusable (or partially salvaged) element, the ET is an expendable element (entirely discarded after one use), and the Orbiter is a reusable (or fully retrieved) element. In Single Stage To Orbit (SSTO) approaches all ground processes relate to this single FE and no integration related ground processes are performed.

The proposed operations assessment model uses a "bottoms up" approach in creating a representation of the space vehicle. Therefore the definition of the space vehicle is based primarily on its FE's, which in turn is based on the definition of its functional systems called constructs. Constructs are created for functional systems such as main propulsion (the engines used during ascent from the Earth to orbit), orbital propulsion (propulsion while in orbit), payload bay, avionics (the type and functions of the electronic systems in the FE), and thermal protection systems. Each construct type is defined by a set of inputs that describe the system in terms of technologies used, size, complexity, maintainability, and reliability. These inputs, and the available options of these inputs, are also
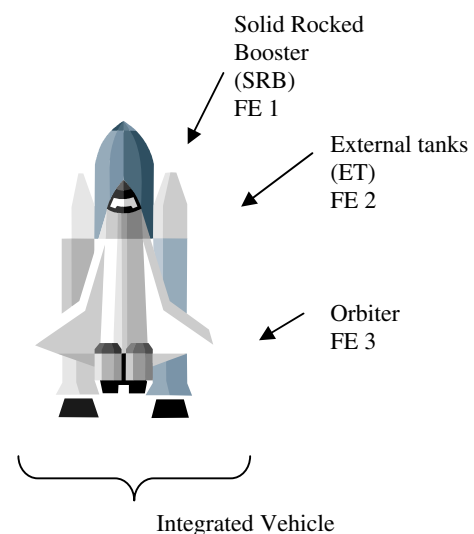

Fig. 2. Shuttle FE and integrated vehicle representation.

knowledge based. Some construct types are of single definition, meaning only one construct of this type can be defined for an FE, while for other types the designer can select an infinite number of same type constructs as part of an FE characterization. Designers have the option of not including particular types of a construct, and therefore showing the possible elimination of all the ground processes directly associated with this system type. For example, a designer can define only one construct related to passengers for an FE (this construct defines the "living" volume, number of crew and passengers, length of stay and other variables), while can define multiple constructs related to main propulsion (as an example an FE could have three large engines and two small engines for ascent propulsion), and can have no payload bay in the design (thus all of those operations are eliminated from the ground operation flow). As illustrated in Fig. 3, the representation of a vehicle system starts with the definition of the constructs, which in turn are the components of an FE. As previously discussed, the FE's make up the Integrated Vehicle (unless is a SSTO). This Lego® like approach to defining an FE provides designers with significant flexibility.

Thermal protection systems (TPS) is a construct familiar to most readers given recent events and relates to the materials used in the outer shell of the Orbiter (or any FE). The Orbiter actually has several types, including various types of "tiles" and "blankets", while the ET has foam insulation (thus in the case of the Columbia disaster, a fragment of TPS from the ET damaged the TPS of the Orbiter, in this case a leading edge). Each of the existing and proposed/new TPS materials is represented in the model as an option for a thermal protection construct of the model, as it has been recognized by operations experts that the choice of TPS material has a direct effect on ground operation's times and cost. Therefore the

model includes a representation of the different material types used for thermal protection and allows users to specify the types to be used in distinct parts of an FE (for example the 'lower' or 'windward' surface of the wings, area of significant heat levels during reentry). The model also allows the designer to define other important parameters of each system, such as the surface area covered by a specific material type. For example, a designer of a new FE can generate a construct which defines the "Top" of the FE to be covered by *Blankets of Type A*, covering a surface area of 2000 sq. ft., and generate a second construct that defines the "Bottom" of the FE to be of *Metallic Tile Type B*, covering a surface area of 2800 ft^2.

Future space vehicles are often defined as multiple stages to orbit concepts like one one used in the Space Shuttle; therefore more than one FE consists of an integrated vehicle. Fig. 4 represents the idea behind the combination of two FE's (e.g. Spacecab or Spacebus: for visualization, visit Bristol Space Limited at http://www.bristolspaceplanes.com/, http://www.bristolspaceplanes.com/projects/spacecab.shtml, and http://www.bristolspaceplanes.com/projects/spacebus.shtml) and the required design information. Both FE's are described by a set of constructs as relatively independent components of an integrated vehicle. FE2 (an FE used only for ascent propulsion and does not reach orbit, thus it has no payload construct, no TPS constructs, no life support, etc.) is described by a smaller number of constructs than FE1 (an Orbiter type FE), and both sets of constructs are part of the integrated vehicle definition. The integrated vehicle definition also needs a separate set of constructs to represent the design approach to the integration of the two FE's. Here designers specify the systems describing the mating systems, and the technical approaches to integrated processes and to launch activities.
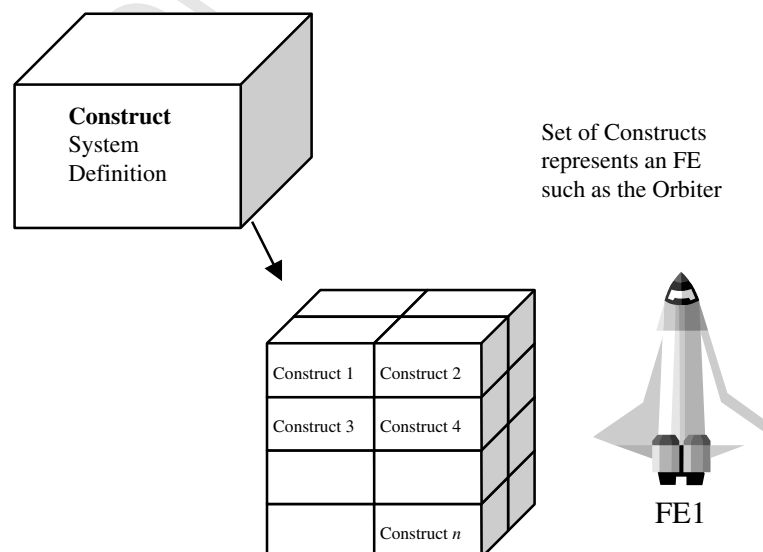

Fig. 3. Modeling approach representation of a Flight Element based on constructs.
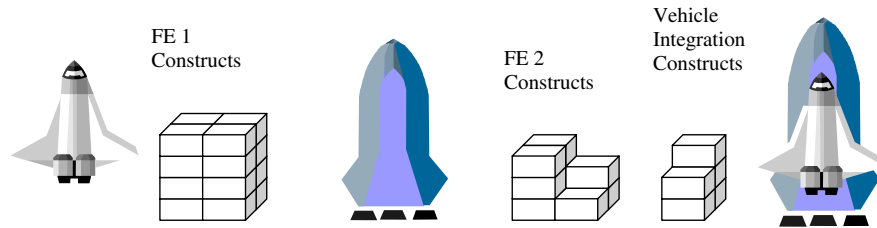
KNOSYS 1557

22 June 2006   Disk Used

ARTICLE IN PRESS

No. of Pages 8, Model 5+

Jayalakshmi (CE) / Karthikeyan (TE)

A.J. Ruiz-Torres et al. / Knowledge-Based Systems xxx (2006) xxx–xxx   5

Fig. 4. Modeling approach representation of the integrated vehicle with multiple FE's based on constructs.

4. Knowledge based operations assessment

The overall strategy of the expert based model is to translate the design of a space vehicle system into the operational requirements of turnaround by imitating the progression used by experts combined with available operational data (the Process Database, and the Operations and Cost Database). The proposed knowledge model combines the FE and vehicle constructs into overall system characteristics that are then linked to ground processes generated from the Process Database. These ground processes are categorized by their relation to major FE and functional systems (the constructs), for example turnaround activities related to thermal protection systems, for ascent propulsion, and for payload processing. The general idea is that based on the design specifications, reliability, maintainability, and supportability "scores" are determined for each construct type (e.g. main propulsion, thermal protection systems) and those are used to modify the ground activities (e.g. main propulsion inspection and maintenance, facility preparation processes). Designs that are simpler, more robust, and/or easier to maintain will result in faster operations, or the elimination of some of the activities. A key strength of this knowledge representation is the ability to represent and manifest as operational effects the complexity, reusability, and operations choices in system design. A designer may add complexity, which is typical of ever-increasing capability, while not necessarily adding to operations costs (consider the evolution to ever more parts and systems within any technology as it advances). The reusability, which is to say maturity of the technology, and reliability, can offset the increase in complexity and yield more productivity. Following on this, the treatment, the operation of the system, can also derive gains representing organizational efficiency related to, yet independent of the product complexity or maturity.

Fig. 5 describes the process of the model and the locations where domain knowledge is used to complete its steps. In Step 1 the designer defines each of the FE's and the integrated vehicle characteristics. Vehicle design knowledge was used to determine the options and inputs required and also to prevent designers from omitting essential systems, for example at least one FE must have a main propulsion system or the vehicle will never be able to depart Earth. However, the system is limited to knowledge determining if a type of system is required, but does not
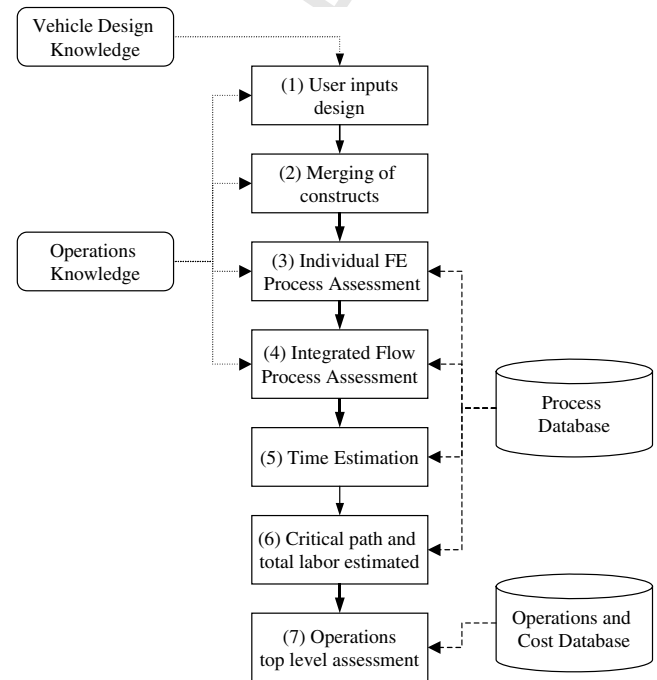

Fig. 5. Process flow for the implemented methodology.

check that the defined construct is capable of achieving lift-off; vehicle designers must use other tools that evaluate flight performance metrics. Step 1 also involves operations knowledge as the input process requires the designer to identify approaches to ground processes that are derived from this knowledge and not considered in the traditional vehicle design process.

Step 2 uses knowledge based equations and logic to assess the complexity, reliability, and maintainability of the individual constructs in the design for each specific FE, combining them by type of construct, therefore all constructs of a particular type in an FE are "merged" and all integration constructs of the same type are merged. Step 3 uses knowledge based functions to link non-integrated FE ground processing activities to all constructs related to an FE and to integration (some integration functions may affect operations associated with the individual FE process flow activities, for example a setup associated with the multi-FE mating process. Step 3 results in a determination of all the *activity characterizations* per FE (at the FE level) for all FE's and ground systems, thus for a ground system, FE1 will have a set of

KNOSYS 1557

22 June 2006   Disk Used

ARTICLE IN PRESS

No. of Pages 8, Model 5+

Jayalakshmi (CE) / Karthikeyan (TE)

6   *A.J. Ruiz-Torres et al. / Knowledge-Based Systems xxx (2006) xxx–xxx*

380 activities and times, and for FE2, a different set of activi-
381 ties and times (unless the related design options are the
382 same). Step 4 is similar to Step 3 but at the integrated
383 vehicle level, in this case determining the integrated
384 ground processing activities, therefore all merged
385 constructs defined for the integrated vehicle system are
386 considered in the analysis of the processes. Step 4 results
387 in a determination of all the *activity characterizations* for
388 integration, thus there is a single set of integrated activi-
389 ties. Step 5 uses the information in the Process Flow Data-
390 base and the activity characterizations from Steps 3 and 4
391 to estimate activity times. Step 6 uses the activity times
392 generated in Step 5 to calculate critical paths at the con-
393 struct level, FE level and integrated vehicle level in order
394 to determine the range of times for complete turnaround
395 operations. Step 7 uses the time data stored in the Opera-
396 tion and Cost Database and design parameters inputted
397 by the designer (in Step 1) to complete the vehicle
398 assessment in terms of launches per year and space lift
399 capability. Future work will expand the actions completed
400 in Step 7 to estimate total labor effort, labors costs, and
401 other operations measures of performance.

402 **5. System implementation**

403   The proposed knowledge based model was implemented
404 in software called the Schedule Activity Generator/Estima-
405 tor (SAGE). The software was developed in Microsoft
406 Visual Basic and its input interface is presented in Fig. 6.

407 The main control interface allows the typical operations
408 such as Save, Open, and New, while multiple application
409 specific controls to run the analysis and create reports are
410 also available. The input interface has icons representing
411 the available constructs. A sample output from SAGE is
412 illustrated in Fig. 7. The report illustrates the top level
413 times for maintenance operations (turnaround), for inte-
414 gration between FE's and for launch operations. The
415 SAGE user can navigate between eight results sets from
416 the Process database by clicking on the top buttons num-
417 bered from one to eight. Users can also get activity details
418 by clicking in any of the graphs as shown in Fig. 8.

419   The SAGE tool has been validated through a series of
420 studies that compare the ground process estimates made
421 by operations experts versus the estimates made by SAGE
422 for a particular vehicle design. The significant benefit
423 attributed to SAGE is the speed of generating the estimates
424 and the fact that it combines knowledge based assessment
425 with historical process data. Most importantly, SAGE pro-
426 vides system designers and teams in early conceptual and
427 collaborative design phases a means by which to gain
428 insight into the diverse possibilities of balancing complex
429 systems, against more reusable systems, against operational
430 efficiencies.

431   SAGE was one of the tools used in NASA's latest archi-
432 tecture analysis, the Exploration Systems Architecture
433 Study (ESAS), completed in 2005. ESAS crafted NASA's
434 strategic and technological plans for the next few decades,
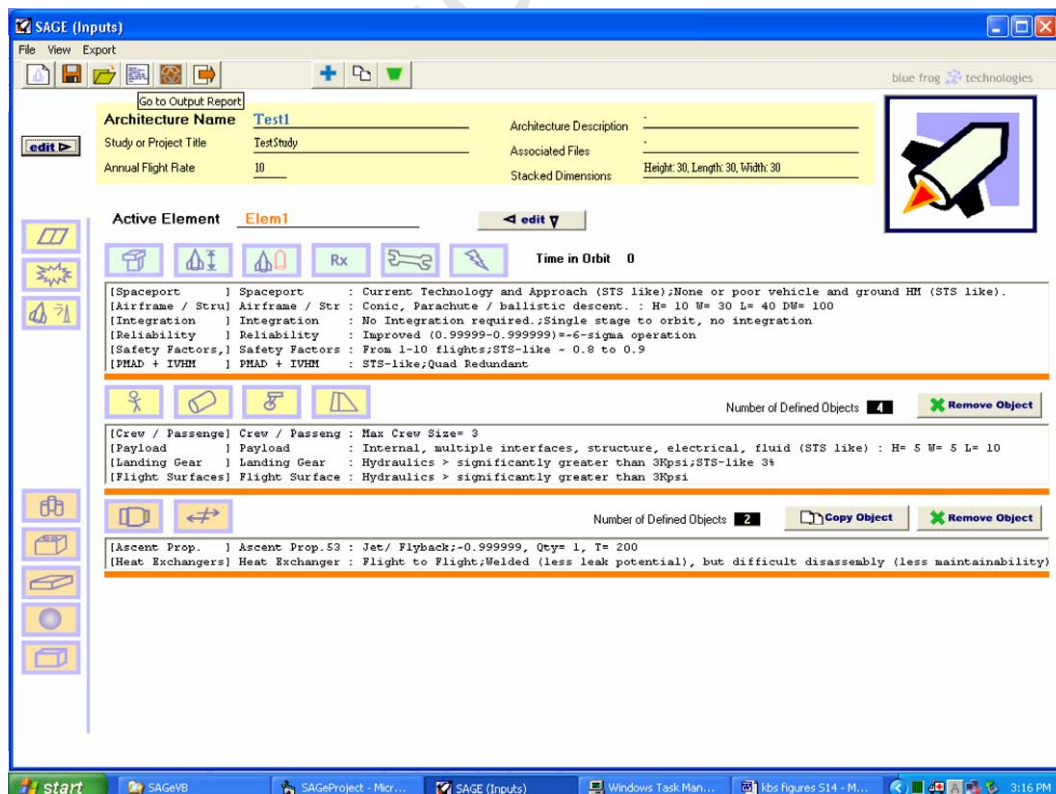435 including the establishment of an infrastructure for space

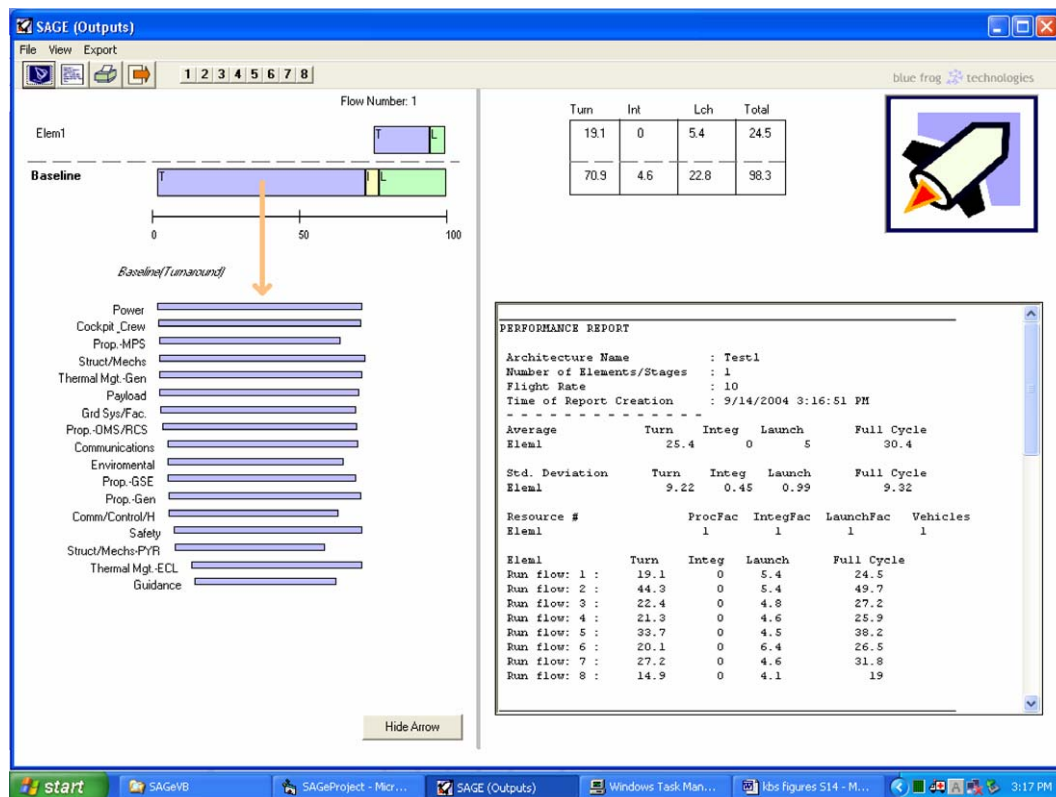Fig. 6. Input interface from SAGE software application.

A.J. Ruiz-Torres et al. / Knowledge-Based Systems xxx (2006) xxx–xxx

7

Fig. 7. Main output form – SAGE software application.
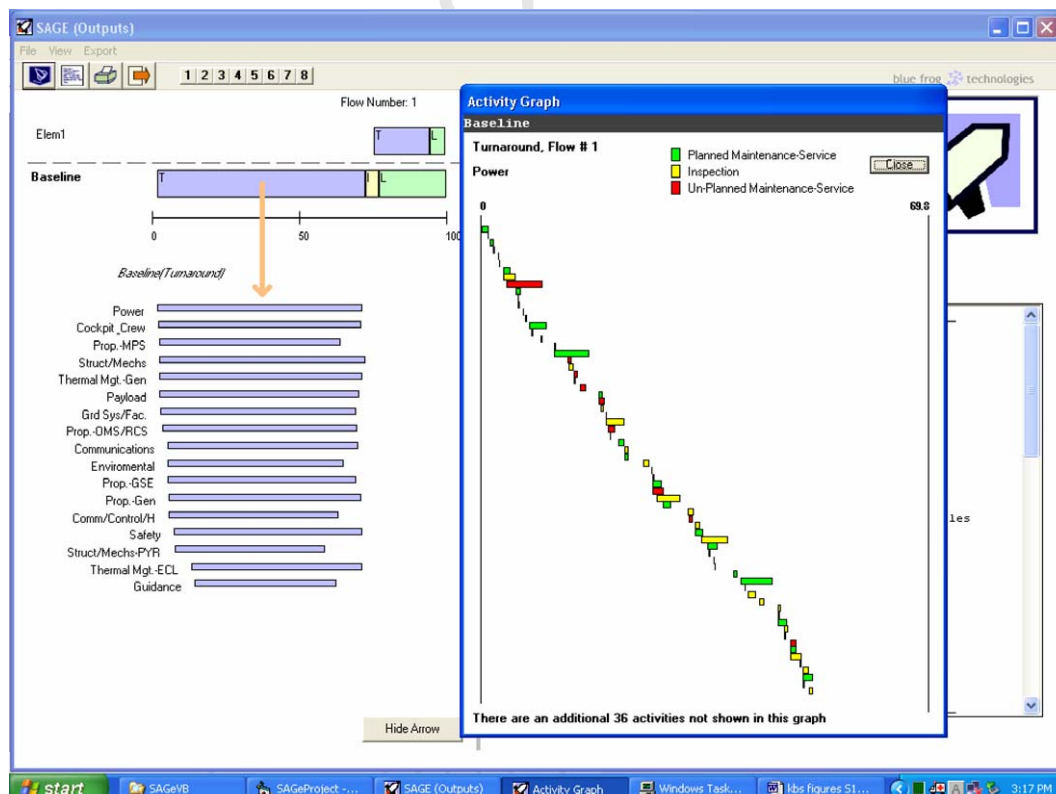
Fig. 8. Activity characterization output form – SAGE software application.

KNOSYS 1557

22 June 2006   Disk Used

ARTICLE IN PRESS

No. of Pages 8, Model 5+

Jayalakshmi (CE) / Karthikeyan (TE)

8   *A.J. Ruiz-Torres et al. / Knowledge-Based Systems xxx (2006) xxx–xxx*

exploration built around the Crew Exploration Vehicle, a reusable vehicle (that transports the crew) in combination with a large solid rocket booster and a second stage as ascent propulsion stages.

6. Conclusions

In this paper, we present a knowledge-based methodology to support the assessment of future space transportation systems. The methodology allows the assessment of highly complex systems using different types of knowledge derived from a variety of operations experts and considering the interaction of diverse vehicle systems. An important element of the methodology is the creation of a knowledge model to represent the vehicle as well as a knowledge model to link the vehicle design to the ground activities and systems. The methodology has been implemented in fully functional software and validated by demonstrating its ability to imitate the assessment of experts.

References

[1] J.C. Mankins, Highly reusable space transportation: advanced concepts and the opening of the space frontier, Acta Astronautica 51 (10) (2002) 727–742.

[2] D.Cope, M. Mollaghasemi, A. Kaylani, A.J. Ruiz-Torres, M.J. Steele, M.L. Cowen, An Integrated Estimation and Modeling Environment for the Design of the Orbital Space Plane, 2005 Winter Simulation Conference Proceedings, 459–465.

[3] D. Stanley, A space transportation architecture of the future, Acta Astronautica 47 (2–9) (2000) 265–274.

[4] T. Dinerman, Space: The Tourist Frontier, Wall Street Journal (Eastern ed.), New York, NY, January 22, 2004, D.6.

[5] R.S. Ryan, J.S. Townsend, Fundamentals and issues in launch vehicle design, Journal of Spacecraft and Rockets 34 (2) (1998) 192–198.